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TIRE FRICTION COEFFICIENTS AND THEIR RELATION TO GROUND-RUN DISTANCE IN LANDING

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ADVANCE RESTRICTED REPORT

TIRE FRICTION COEFFICIENTS AND THEIR RELATION TO GROUND-RUN DISTANCE IN LANDING

By F. B. Gustafson

SUMMARY

A summary of published information on braking friction coefficients is presented. An analysis is included which indicates that the magnitude of the friction coefficient available will affect the technique required for obtaining the shortest ground run only under extreme conditions. In this connection, technique refers to the choice between utilizing air drag and ground friction through choice of attitude. The analysis further shows that the landing attitude is almost never the attitude for the shortest ground run. A chart is presented for rapid estimation of ground-run distance for any set of values of friction coefficient, airplane attitude, initial drag-weight ratio, and initial velocity. Sample studies are presented for high- and low-wing loadings.

INTRODUCTION

At the suggestion of Dr. Edward Warner of the Civil Aeronautics Board, the NACA has recently reviewed available information on tire friction coefficients, with particular reference to the effect of field condition on coefficients available for braking. A summary of the information found on braking friction coefficients is included in this report.

An analysis was made to indicate the extent to which a variation in landing technique, from consideration of choice between utilizing air drag or ground friction through choice of attitude, becomes desirable as a result of changes in field conditions. For this purpose it was assumed that the choice was not influenced by nosing-over tendencies. It was further assumed that the load carried

by unbraked wheels was negligible. This analysis indicated that only under extreme conditions would the technique required for obtaining the shortest ground run be affected by the value of the friction coefficient. The analysis did show, however, that the landing attitude is almost never the attitude for shortest ground run. A chart has been prepared for rapid estimation of ground-run distance for any set of values of friction coefficient, airplane attitude, initial drag-weight ratio, and initial velocity. Sample studies of ground-run distance are included for both high- and low-wing loadings.

BRAKING FRICTION COEFFICIENTS

Sufficient published information was found on the effect of surface type and condition and of tire tread on braking friction coefficients to establish the limits imposed for most of the combinations normally anticipated. Most of this information resulted from highway research, and these results are directly applicable to airplanes during ground runs. While all available data of this nature were reviewed, references 1, 2, and 3 cover the subject well; other consulted sources largely served to check rather than to add to the information contained in these papers.

On hard surfaces, such as concrete or asphalt, the coefficient available when the surface is clean and dry is likely to be 0.7 or higher, even for tires without tread. Although values above 1.0 are seldom reported for speeds above 10 or 15 miles per hour, coefficients in the neighborhood of 0.9 are common. The adverse conditions, however, normally govern the permissible length of run. The most common adverse condition is wetness of the surface. For smooth-tread tires skidding straight ahead at speeds in the neighborhood of 30 to 40 miles per hour, most highway surfaces, including Portland cement concrete in both smooth and rough condition, give coefficients between 0.3 and 0.4 when wet. Reference 1 gives fairly complete data on coefficients for different surfaces. The following coefficients of sliding friction for smooth-tread tires skidding straight ahead on a wet surface at speeds of about 30 or 40 miles per hour are taken from this source:

Surface	Coefficient
Penetration macadam, soft seal coat Fine aggregate asphalt plank Wooden plank Steel traffic plates Mud on concrete	All values of coeffidient below 0.3
Ohio tar macadam High-type asphaltic pavements Iowa untreated gravel, loose Cinders, loose	All values of coefficient above 0.4

Values for an incipient skid are usually higher than the foregoing values for sliding friction. The effect of tread is quite pronounced on most hard surfaces when wet, the coefficient for a treaded tire being of the order of one-quarter greater than the coefficient for a smooth tire on the same surface.

Ice, including snow with an icy surface, provides the limiting condition for any field where such a condition is anticipated. Values of braking coefficient of 0.05 and 0.06 for tires on ice have been reliably reported but are thought not to be the lowest values obtainable. An approximate normal value is 0.10. Temperature has a very important effect on the coefficient for clean ice, the value dropping rapidly as the surface temperature rises toward the melting point.

The spreading of abrasives on ice is quite effective. Some information on this point is given in reference 1, and a fairly thorough treatment may be found in references 2 and 3. It appears that the value with abrasives is quite independent of temperature and that a coefficient of the order of 0.20 can be quickly reached by thoroughly practicable methods of spreading. Reference 1 states that a value of 0.42 was reached several days after the application of cinders, as a result of their having become embedded.

The importance of the good performance credited to abrasives is enhanced by the fact that tire tread does not offer even a potential solution to the problem of stopping on ice and packed snow. Although tread provides a marked advantage over smooth tires on nearly all bare, wet roadway surfaces, as has been already noted, the effect on ice or snow is quite different. References 2 and

3 show that on ice at a temperature near freezing, tires with tread have higher braking coefficients than smooth tires but, at lower temperatures, smooth-tread tires give higher values. On loose snow a lug tread shows advantages, but on packed snow stopping distances are usually shorter with smooth tires than with treaded tires. Values for an impending skid are likely to be somewhat better for the treaded tire than for the smooth tire on either ice or packed snow, but with brakes locked the grooves fill and the coefficients drop. In brief, the differences produced by tread on packed snow and smooth ice are small, and whenever ice and snow are anticipated, the limiting condition will not be appreciably altered by the use of tread on tires.

In spite of the predominant use of hard-surfaced runways, landings on turf must still be given consideration; for example, for temporary or emergency airports. Experimental values for braking friction coefficients on grass are rather scarce. From horizontal and vertical accelerations recorded at contact during a series of landing tests conducted by the NACA on the turf surface at Langley Field, Va., it is concluded that such a surface when in typical condition has a friction coefficient of about 0.5. The highest continuous deceleration recorded during fully braked runs was 0.42, and it is felt that this value represents very nearly the friction coefficient available during that run.

For a turf field when wet, very little data are available. The values found do not appear to be conclusive and more information on this point is desired.

Information is also lacking on the effects of high speed and of tire size on braking coefficients. The values given, with the exception of the data obtained from NACA landing tests, are for automobile tires tested at speeds not exceeding 45 miles per hour. The evidence at hand, however, does not point to the likelihood of any radical changes in the general conclusions when these factors become known. Likewise, although reference 1 shows an increase in friction coefficient on wet concrete with a decrease in temperature, introduction of this factor would appear to constitute a refinement rather than a fundamental revision.

By way of a general conclusion, it is believed from this study that, on a well-maintained airport, a minimum value of the coefficient of braking friction of 0.20

should be expected. Lower values, such as would exist on newly formed ice prior to treatment, should be considered as present under emergency conditions. Where ice is not expected, the minimum value should be 0.30, provided the surface has been properly chosen and is kept free of mud; the minimum value may, of course, be still higher, depending on the particular surface used.

APPLICATION OF FRICTION COEFFICIENTS

TO CALCULATION OF LANDING DISTANCE

Two forces add together to stop the airplane: air drag and wheel friction. The manner in which these forces change during the ground run is illustrated in figure 1. In the preparation of figure 1 the airplane was assumed to make the run at an angle of attack close to the stall, and it was further assumed that a coefficient of friction between wheels and ground of 0.4 was utilized throughout. By a quick reduction of the angle of attack of the airplane following contact, greater use may be made of wheel friction; this condition is plotted in figure 2. A comparison of figure 2 with figure 1 shows that reducing the angle of attack after contact sacrifices less in air drag than it gains in ground friction force, for the conditions assumed, and hence will produce the shorter run.

If the friction coefficient is sufficiently low, the advantage will obviously lie in the reverse procedure; that is, in making the greatest possible use of air drag. Figure 3 was prepared to indicate the conditions under which this result might be expected. It illustrates, for the sample polar shown in figure 4, the ratio of drag change to lift change for any instantaneous change in attitude between the limits represented by $C_L = 0$ and and $C_L = C_{L_{max}}$. Figure 3 was drawn for the polar for flaps extended; for values of $C_L/C_{L_{max}}$ lower than 0.5, it also applies to the polar for flaps retracted. When an increase in angle of attack gives a ratio of drag change to lift change greater than the value of friction coefficient available, the use of the higher angle of attack will result in greater total deceleration. Likewise, if a decrease in angle of attack gives a ratio less than the value of friction coefficient available, the use

of the lower angle of attack will result in greater total deceleration. For example, assume that the choice is between an angle of attack represented by $C_L/C_{L_{max}} = 0.9$ and an angle of attack represented by $C_L/C_{L_{max}} = 0.4$. Changing from one angle of attack to the other gives a ratio of drag change to lift change of 0.13. If the friction coefficient is less than 0.13, the use of the higher angle of attack will therefore result in a greater total deceleration. Inasmuch as the lowest value of friction coefficient expected on a well-maintained airport is 0.20, the higher angle of attack will insure the quicker stop only under emergency conditions. As another example, assume that the friction coefficient available is 0.20 and that a value of $C_L/C_{L_{max}}$ of 1.0 can be used. Figure 3 shows that, if any value of $C_L/C_{L_{max}}$ less than 0.5 can be reached, the use of this lower angle of attack will produce the greater deceleration.

Examination of figure 3 shows that the greatest deceleration will always be present at one of the two extremes; that is, either at the highest or the lowest angle of attack that can be reached. This result will be true for any polar that is concave upward throughout because operation at intermediate angles of attack is then equivalent to operation near maximum L/D, an obviously undesirable condition. With this fact in mind, the second example given yields two interesting conclusions. First, since an angle of attack below $C_L/C_{L_{max}} = 0.5$ can be reached with most airplanes and since the friction coefficient is nearly always above 0.20, it is concluded from figure 3 that only under extreme conditions will the magnitude of the friction coefficient available affect the technique required for obtaining the shortest ground run. In other words, the best technique nearly always consists in making the greatest possible use of ground friction rather than of air drag. Second, since an airplane seldom lands at the lowest angle of attack that can be maintained during the ground run, especially if the pilot keeps the approach speed down for the sake of a short run, it is likewise concluded that the landing attitude is rarely the attitude for the shortest ground run.

It should be pointed out that, in the case of conventional gear, another factor enters into the choice of attitude; namely, the tendency of the airplane to nose

over. After the air forces have dropped off, it is desirable to have the tail low enough to permit fullest possible use of the available wheel-friction force. This consideration obviously does not arise in the case of the tricycle landing gear.

Conclusions drawn from the study represented by figures 1, 2, and 3 are purely qualitative. In order to enable calculations to be made of the ground-run distance for any given value of friction coefficient, a general equation has been derived and a convenient form of chart prepared. The equation and the chart have been made to include the effect of angle of attack directly. This procedure was adopted not only because of the importance of attitude suggested by the qualitative study but also because considerable change in attitude following contact is feasible, and some change inevitable, with the tricycle landing gear.

The decelerating force at a given instant will be the sum of the air force and the wheel friction force,

$$a = \frac{F}{M} = \frac{\frac{D}{L}L + \mu(W - L)}{W/g}$$

where

W weight

D drag

L lift

μ friction coefficient between airplane and ground

and

k ratio of lift at start of run to weight (L_1/W)

V velocity, feet per second

Assume C_L and C_D to be constant during the run. Use the subscript $_1$ to represent conditions at the start of the run. The expression $kW\left(\frac{V}{V_1}\right)^2$ can be substituted for

L, and $D_1 \left(\frac{V}{V_1}\right)^2$, for D. This procedure gives

$$a = g \left[\frac{D_1 \left(\frac{V}{V_1}\right)^2}{W} + \mu \left(1 - \frac{kV^2}{V_1^2}\right) \right]$$

By substitution in the equation

$$s = \int_{V=0}^{V_1} \frac{VdV}{a}$$

where s is the distance covered, and by integration, the expression becomes

$$s = \frac{V_1^2}{2g\left(\frac{D_1}{W} - k\mu\right)} \log_e \frac{\frac{D_1}{W} + \mu - k\mu}{\mu}$$

For a given value of L_1/W or k the average deceleration, and hence the distance for an airspeed equal to 1 for any given ratio of D_1/W to μ, is proportional either to D_1/W or μ. The result is shown in figure 5, in which the value of $D_1/W + \mu$ has been plotted against the distance s' for $V_1 = 1$ and $\mu = 1$; curves are shown for values of angle of attack, as represented by k, from $k = 0$ to $k = 1.0$.

A value of ground-run distance can be calculated from this chart as follows: First, calculate the ratio $D_1/W + \mu$. This step is most easily taken, as a rule, by the use of the drag coefficient and the lift coefficient that would be required for support at the initial speed, or

$$\frac{D_1/W}{\mu} = \frac{C_D}{\mu\left[C_{L_{max}}\left(\frac{V_s}{V_1}\right)^2\right]}$$

where V_s is stalling speed. Then, calculate the value of k, which is simply the lift coefficient divided by the lift coefficient that would be required for support at the initial speed, or

$$k = \frac{C_L}{C_{L_{max}}\left(\frac{V_s}{V_1}\right)^2}$$

Using these two values, read the value of s' from the chart. Multiply s' by the square of the initial speed and divide by the value of μ. The answer is the ground-run distance.

This chart should be useful for design estimates for both airplanes and airports, inasmuch as it is possible to examine the effect of changes in ground-friction coefficient, air drag, and angle of attack, as well as initial velocity, either singly or in combination.

SAMPLE STUDIES

The significance of the ground-friction coefficient and of the related problem of angle of attack during the ground run cannot be precisely stated except for specific cases. For this reason, the following sample study is presented.

It is assumed that a coefficient of friction of 0.4 is utilized between tires and ground. It is also assumed that brakes are used on all wheels. The effect of the time required to change the angle of attack following contact has been indicated by making calculations for zero transition time and for a 2-second transition period. The conditions, the encircled numbers used to represent them, and the corresponding values of lift and drag assumed are as follows:

(1) Airplane at stall; $C_{L_{max}} = 2.0$, $C_D = 0.30$

(2) Thrust axis horizontal, flaps not retracted;

$$C_L = 0.93,\ C_D = 0.12$$

(3) Thrust axis horizontal, flaps retracted;

$$C_L = 0.33,\ C_D = 0.025$$

When a transition from one angle of attack to another is involved, both encircled numbers are used. (See fig. 6.) Thus, (1) - (2) means that contact was made at condition (1) and a transition made to condition (2).

The runs with zero transition time were calculated by means of figure 5 in the manner already explained, using the lower angle of attack as the initial condition. For the runs with 2-second transition period, the distance covered and the velocity lost during this period were calculated on the basis of two 1-second intervals, assuming that half the decrease in angle of attack had been attained during the first second. Successive approximations were used to determine the deceleration during each second. The rest of the run was calculated by means of figure 5, using the speed and the angle of attack at the end of the 2-second period as the initial condition.

The calculations were carried out over two ranges of wing loading to indicate the effect of this factor. The values obtained are plotted against effective wing loading in figures 6 and 7. The effective wing loading $W/\sigma S$, where W/S is the wing loading in pounds per square foot and σ is the density ratio, was used so that a single plot could be readily used for any density altitude. The effect of change of angle of attack, and of transition time required for this change, on ground-run distance is summarized in figure 8, in which average deceleration is plotted against reduction in lift coefficient following contact for the lowest and highest wing loadings covered by figures 6 and 7, respectively. The effect of a fixed transition time is shown to be appreciably less at the higher value of contact speed. Further, in every case examined in this study, the effect of reduction in angle of attack at or following contact is shown to be a reduction in ground-run distance.

CONCLUDING REMARKS

The values found for the braking friction coefficients of smooth-tread tires on various surfaces indicate that such coefficients under adverse conditions, including rain and snow, are commonly above 0.2 and that the outstanding exception, fresh ice, can be raised to this value by appropriate treatment. Values for smooth-tread tires on wet surfaces commonly fall between 0.3 and 0.4. Exceptions are common enough and the divergences in values are wide enough to necessitate attention to specific values in designing or rating airports when the landing run may be critical.

The analysis of the effect of low values of braking friction coefficient on the relative merit of tail-high and tail-low attitudes during the ground run indicates that, if the friction coefficient available is greater than 0.2, the technique should be directed toward utilizing braking friction rather than air drag. For values below 0.2 consideration of the individual case is necessary.

The chart presented for estimation of ground-run distance should facilitate quantitative study of the effect of changes in ground friction for specific cases. Except where full knowledge of applicable assumptions exist, however, it should be used chiefly to determine relative rather than absolute values.

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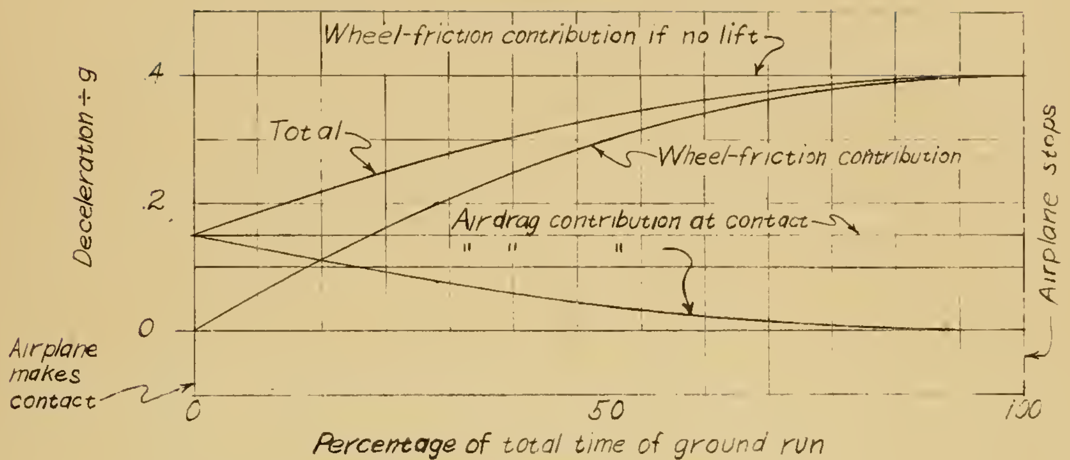

Figure 1.- Variation of air and wheel friction forces during ground run at constant angle of attack.

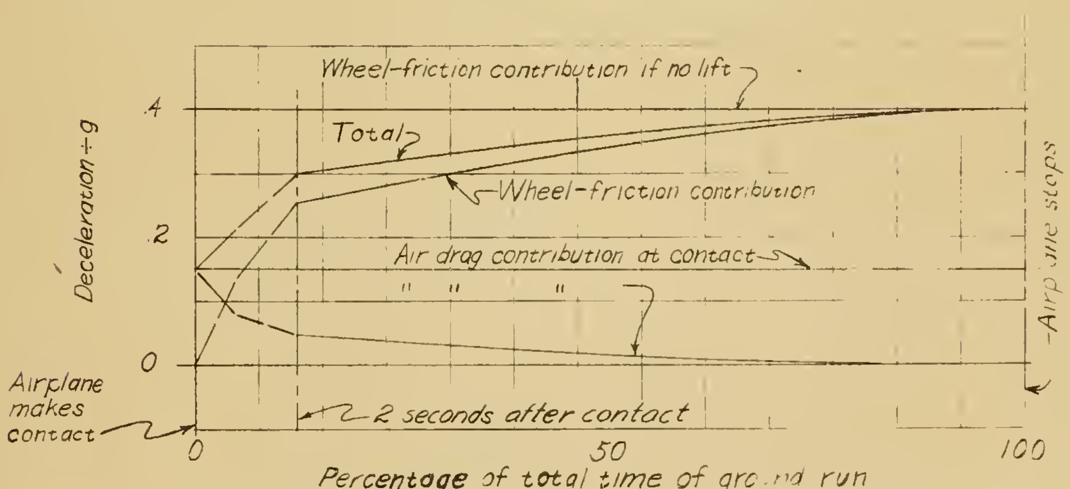

Figure 2.-Variation of air and wheel friction forces during ground run when angle of attack is reduced quickly after contact.

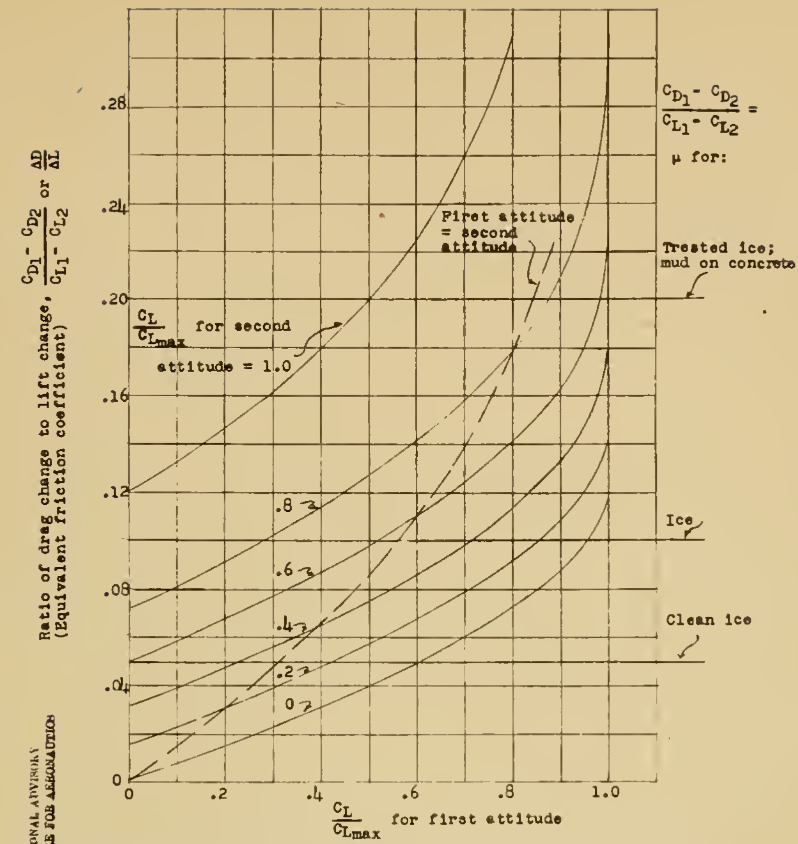

Figure 3.- Chart to facilitate comparison of any two attitudes between zero lift and the stall, for any given instant, to show which attitude will give the greater deceleration with any assumed friction coefficient. See polar of figure 4.

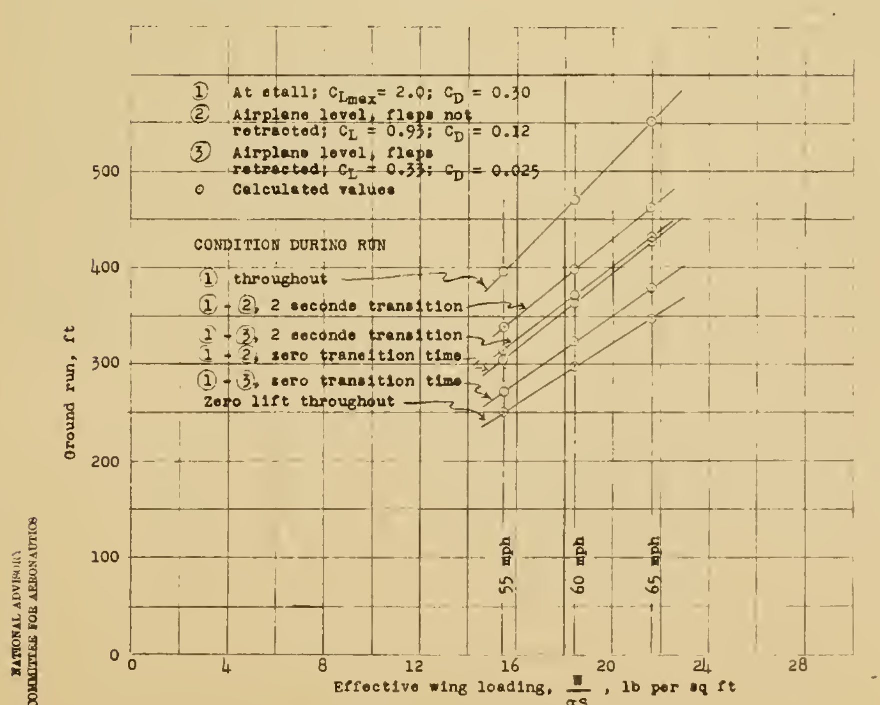

Figure 6.- Variation of ground-run distance over a range of low wing loadings for several ground-run procedures. μ = 0.4.

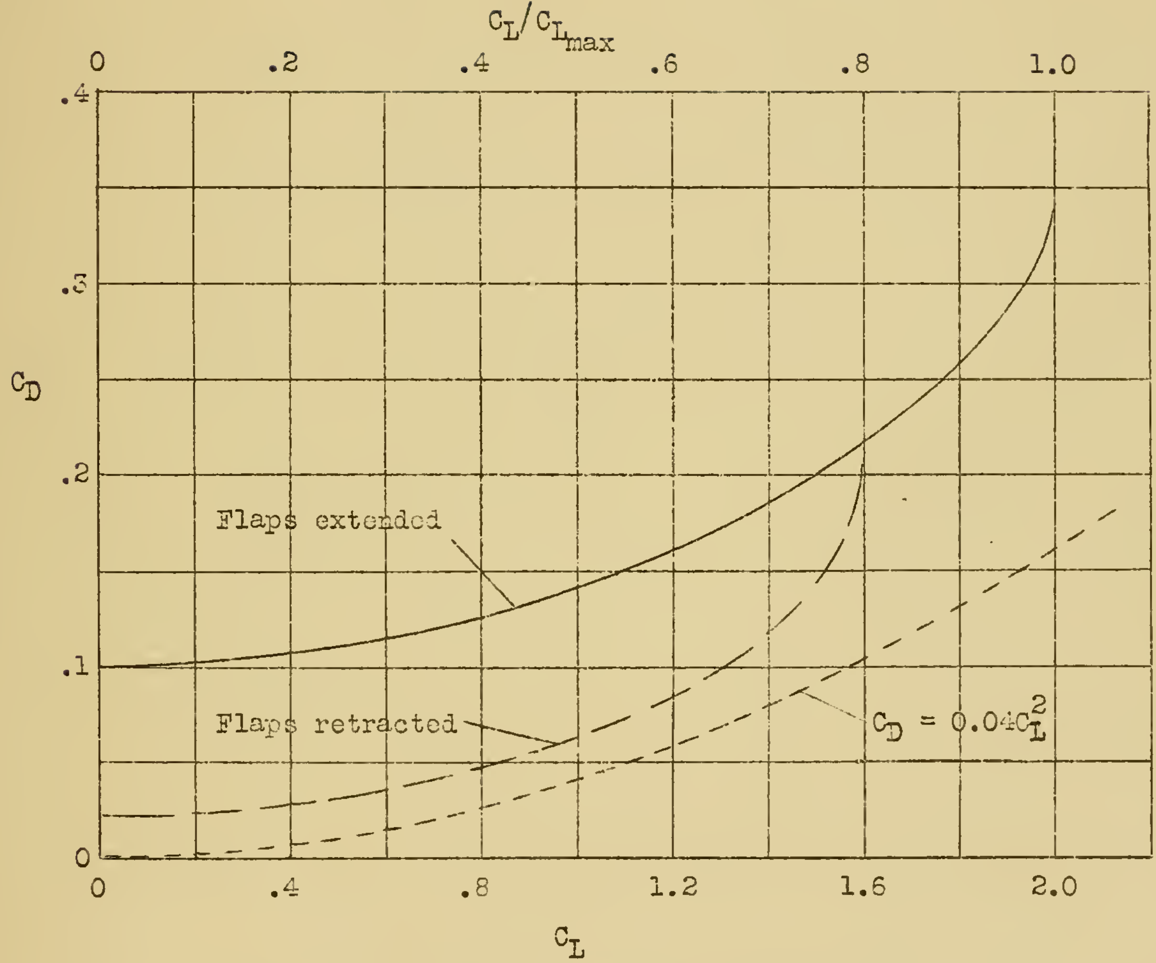

Figure 4.- Polar curve assumed for preparation of figure 3.

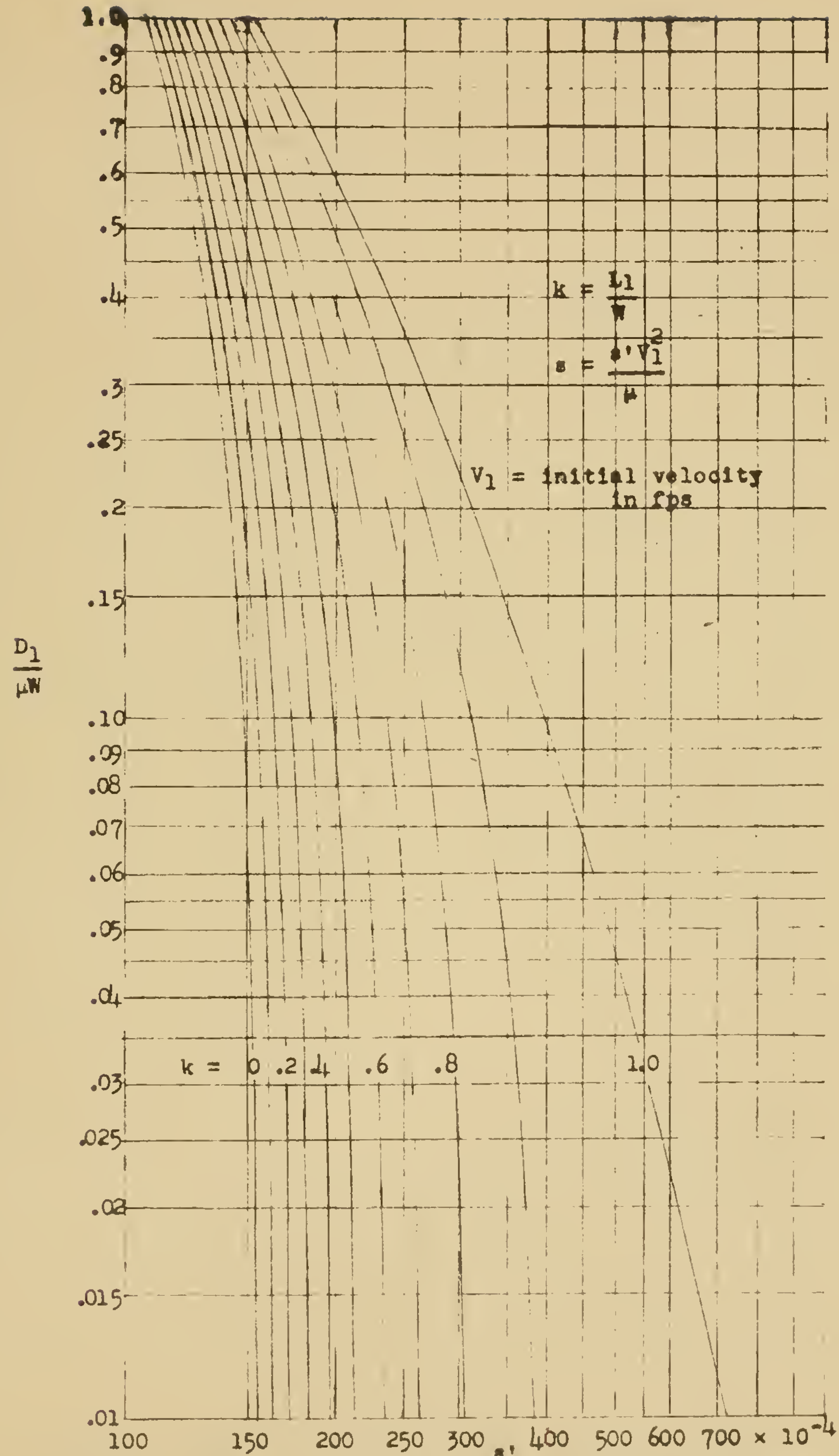

Figure 5.- Chart for estimation of ground-run distance.

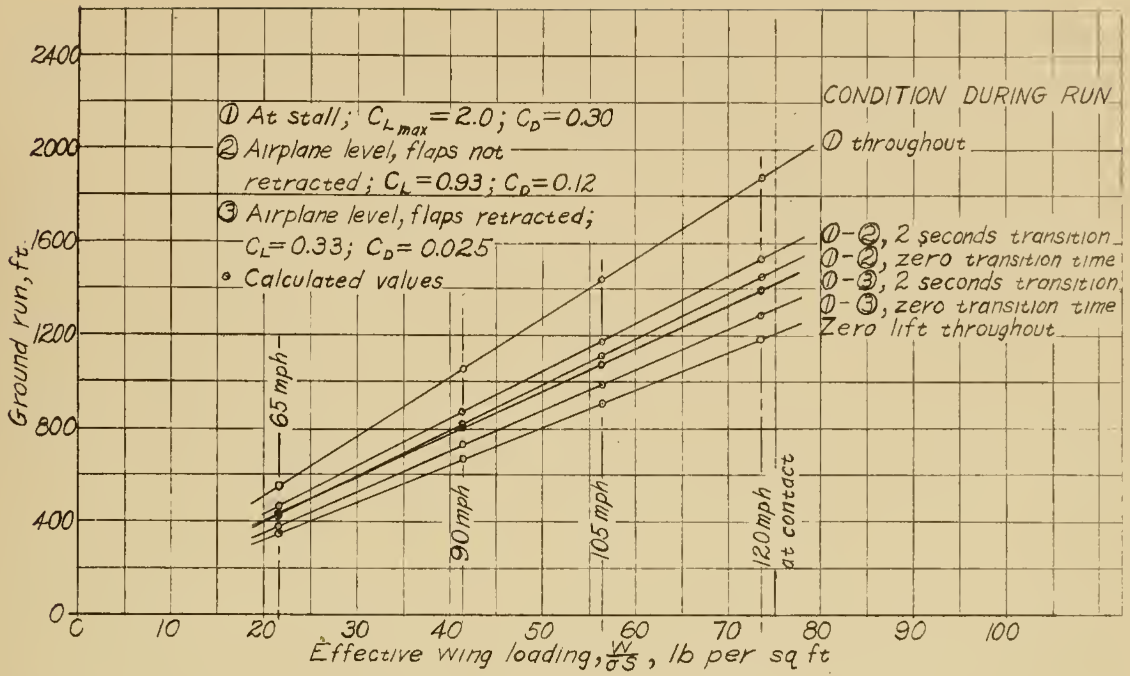

Figure 7.- Variation of ground-run distance over a range of high wing loadings for several ground-run procedures. $\mu=0.4$.

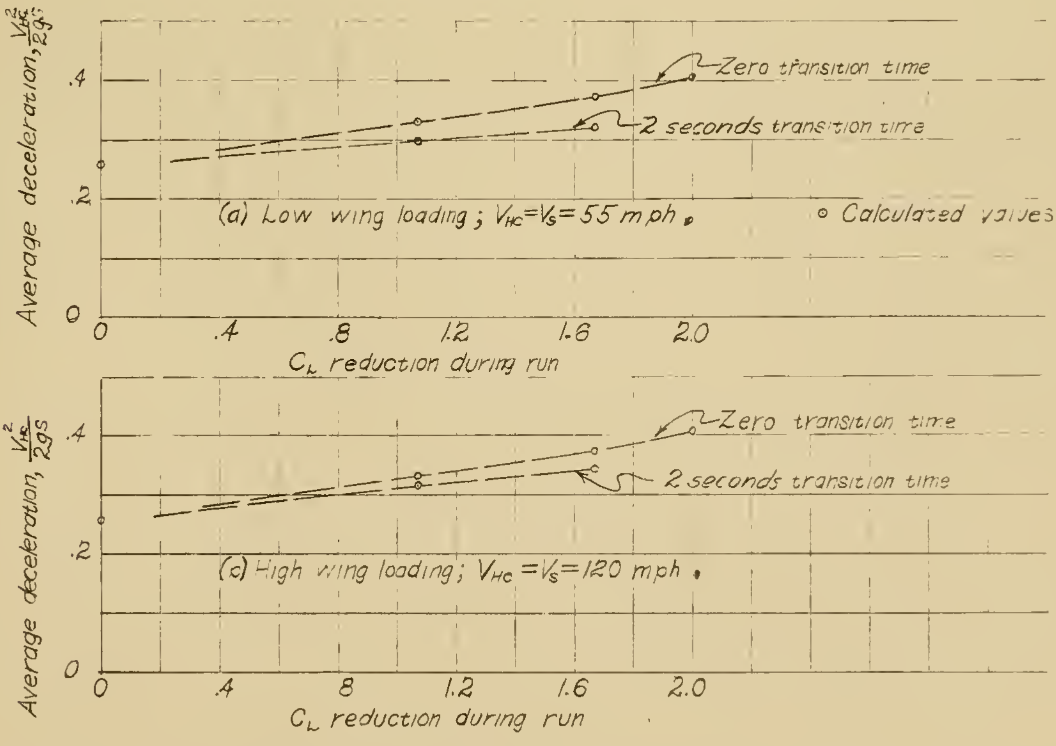

Figure 8.- Effect of C_L reduction at or immediately following contact on average deceleration during ground run. $C_{L_{max}}=2.0$; V_{HC}, horizontal velocity at contact.

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